SSCL-N-846

The Development of a Positron Ionization Gauge

F.M. Jacobsen, M. Strongin, and M.W. Ruckman

Department of Physics
Brookhaven National Laboratory
Upton, NY 11973

A. Wiess

Department of Physics
The University of Texas at Arlington
Arlington, Texas 76019

W.C. Turner

Superconducting Super Collider Laboratory*
2550 Beckleymeade Ave.
Dallas, TX 75237

January 1994

*Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

The Development of a Positron Ionization Gauge

F.M. Jacobsen, A. Wiess, M. Strongin, M.W. Ruckman, and W. C. Turner

Abstract

We present a method by which gas pressure (density) can be measured by positrons. The process to monitor is the formation of positronium, Ps, via electron capture by the e^+ from the rest gas molecules. The Ps signal which is proportional to the gas density is obtained from the annihilation photons which are emitted when the Ps atom decays. By this method it is not necessary to have access to the vacuum system in question other that having the possibility of passing a positron beam through it. Also the present method is fully UHV compatible. In its simplest version pressures below 10^{-8} torr (at room temperature) can be measured within a reasonable time. Techniques are discussed which will significantly improve the sensitivity of the present ionization gauge.

1.0 INTRODUCTION

Under certain circumstances one may be interested in knowing the pressure in a vacuum system at a place where it is difficult or impossible to use a standard ionization gauge. In such cases a negatively charged ion beam could be used and the pressure could be monitored by observing the degree of neutralization of the ion beam. However, the use of ion beams may cause problems as these are intrinsically none UHV compatible. An alternative method is to use a low energy positron beam and monitor the yield of positronium, Ps, due to e^+ collisions with the rest gas. The Ps formation signal is obtained from the annihilation photons which are emitted when the Ps atoms decay. The Ps atom can be formed in a singlet state which decays into two back-to-back 0.511 MeV gammas or in a triplet state, which in vacuum, annihilates into three photons. For most practical cases, however, the triplet Ps will interact with the vacuum tubing with the result that it decays into two 0.511 MeV photons. The average drift length of triplet Ps is about $6 \times \varepsilon_{Ps}^{1/2}$ cm, where $\varepsilon_{Ps}^{1/2}$ is the kinetic energy of the Ps atom in eV. To detect the formation of Ps, two NaI detectors facing one another and placed outside the vacuum system are used to register the two annihilation photons in coincidence.

The specific reason for designing and using the positron ionization gauge is to be able to measure the pressure inside the Superconducting Super Collider (SSC) beam tubing during simulated operation. It is recognized that the desorption of hydrogen from the helium-cooled wall by synchrotron radiation generated by the 20 TeV proton beam significantly increases the base pressure in the collider. The gas density in the collider must be kept below 3×10^8/cc to ensure a design beam lifetime of 300 hours.

A brief description of how to generate the needed low energy e^+'s is given in Section 2 while the results of an earlier test experiment are presented in Section 3. In Section 4 the design of the present e^+ beam is described and its performance in its simplest version is discussed with respect to its sensitivity to pressure measurements. In Section 5 we discuss a more advanced version whereby at least an order of magnitude increase in pressure sensitivity can be obtained. Section 6 contains a discussion of the signal to noise ratio along with a description of how the density measurements can be made absolute. Section 7 includes a summary and concluding remarks.

2.0 GENERATION OF LOW ENERGY POSITRON BEAM

The purpose of this section is to give a brief description of how low energy e^+ beams are generated. In a recent review paper[1] which contains references to the original works more detailed information can be found on low energy e^+ physics.

The most common way to generate a low energy e^+ beam is to use ^{22}Na to provide a broad energy spectrum of β^+ particles. The most probable energy of the β^+'s is about 200 keV with the end point energy being 540 keV. A tungsten moderator (a 1-μm thick film) which has a negative e^+ workfunction (affinity), ω, is placed in the front of the ^{22}Na source. A few % of the β^+ will stop and thermalize in the moderator and a fraction of these positrons diffuse to the moderator surface opposite to the ^{22}Na source where they are emitted into vacuum with a kinetic energy equal to $-\omega$. Typical moderation efficiencies taken as the number of low energy e^+ to the total number of β^+ ranges from $1–5 \times 10^{-4}$ (see Reference 2). If solidified noble gases are used to moderate the β^+'s it is possible to enhance the moderation efficiency by 1 to 2 orders of magnitude.[3]

The low energy e^+ which are emitted from the moderator are accelerated and transported by standard techniques. In our case, an axial magnetic field, B, generated by a set of Hemholtz coils is used to guide the e^+ to the interaction region. In order to separate the moderated e^+ from those β^+ not stopped in the tungsten foil the beam is passed through one or two Wien filters ($E \times B$). Figure 1 pictures the main components for a low energy e^+ beam using magnetic transport.

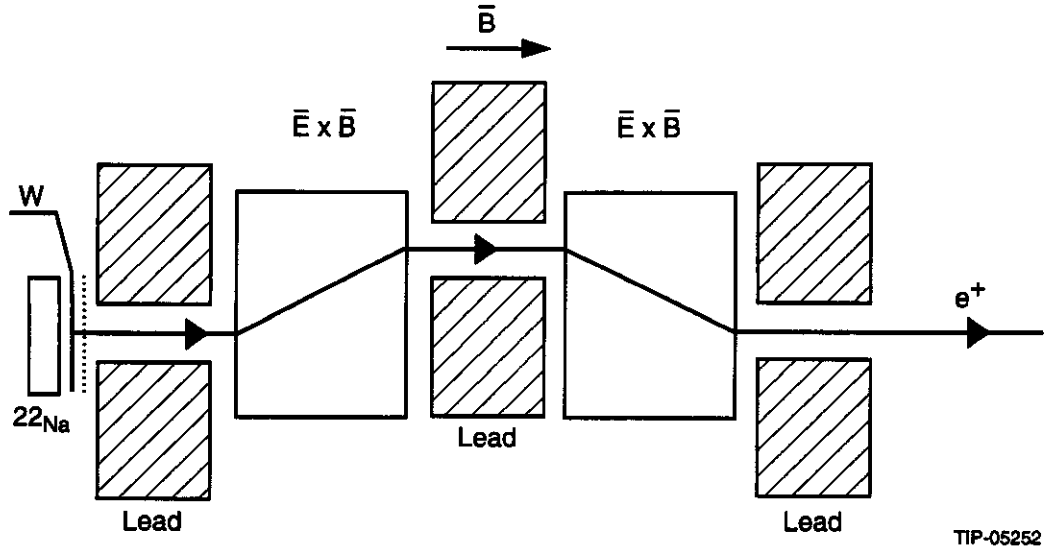

Figure 1. Main components of a magnetically guided low energy positron beam.

3.0 TEST EXPERIMENT

An experiment was carried out on an existing e^+ beam line using magnetic transport at Brookhaven. This beam line delivers 10^6 low energy e^+ sec^{-1}. The experimental setup is outlined in Figure 2. A 30 eV e^+ beam is passed through a 100-mm diameter drift tube. Part of the drift tube is viewed by two 3 in. × 3 in. NaI detectors facing one another and the coincidence counts of these detectors are measured as a function of the H_2 density in the drift tube.

Figure 3 shows a typical signal from a Time-to-Amplitude Converter with one of the NaI supplying the start and the other the stop pulse. The FWHM is about 20 nsec. In Figure 4 the coincidence count rate is plotted as a function of the H_2 density. The pressure reading of the ionization gauge was converted into density as $n = 4 \times P/(kT)$, where P is the pressure; k, Boltmann's constant; and T, the temperature. As observed, the results of Figure 4 contains a large background contribution which is not a result of random coincidences but is due to the scattering of the 1.28 MeV photons from a nearby 45 mCi ^{22}Na source used from another experiment. This background will not be present in the measurements of the H_2 (or H) density in the SSC tubing.

When this signal background is subtracted from the raw data we obtain the results represented by the triangles. At a density of 6×10^8/cc we obtain a count rate of 40 $hour^{-1}$ for the present configuration. The random coincidences will contribute 2 event $hour^{-1}$ within the peak region. The H_2 pressure sensitivity can be further improved by lowering the threshold for the detection of the annihilation photons. In the test experiment this was not possible due to signal contribution from the extra ^{22}Na source which was present. However, one additional measurement was made at the highest gas density in which the discriminator thresholds were lowered with the result that the signal rate increased by a factor of 4.

The cross-section for Ps formation,[4–5] σ_{Ps}, in e^+ collisions with H_2 and H are shown in Figures 5 and 6. A representative value for σ_{Ps} equals 2×10^{-16} cm^2. The signal rate, R, can be calculated as

$$R = 2\Omega n \sigma l I_{e^+} / 4\pi \quad (1)$$

where Ω is the smallest solid angle of the two NaI detectors, n is the gas density, l is the length of the interaction region as viewed by the detectors and I_{e^+} represent the number of e^+ sec^{-1}. The factor of 2 comes about because the formed Ps atoms result in the emission of two gamma rays. Note, since the angle between the emission of the two annihilation photons is close to 180° only one solid angle enters into Eq. (1). Also the detection efficiency (disregarding solid angle effects) of the NaI detectors can be made close to 1 and, therefore, does not enter into Eq. (1).

If we represent l by the detector radius we have $R = 450\ \text{hour}^{-1}$ at a density equal to 6×10^8/cc. The difference between the calculated rate and that measured is, as discussed above, mainly due to the high threshold used when detecting the annihilation photons. However, a factor between 2 and 3 is missing. Four effects may account for this discrepancy. It is possible that some of the triplet Ps may decay by three photons annihilation due to the large diameter of the drift tube whereby the detection efficiency decreases. Also, the signal rate depends on the alignment (which may not have been perfect) of the beam in the drift tube. Furthermore, the Hydrogen pressure was measured about 0.5 meter away from the position of the NaI detectors which results in a somewhat lower gas density than indicated by the pressure reading. Finally, the Ps formation cross-sections as measured by various groups are not absolute.

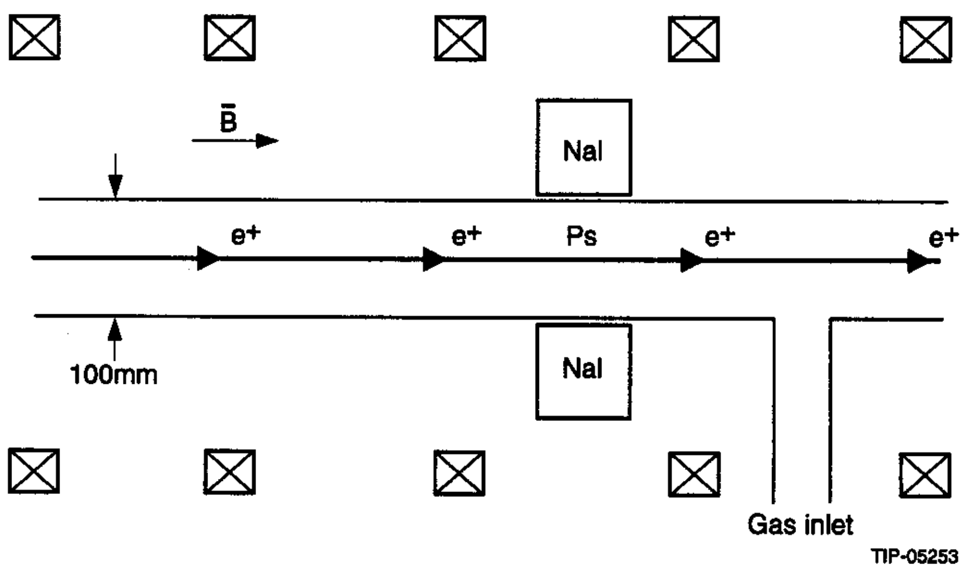

Figure 2. The setup for the test experiment to determine the density of Hydrogen by monitoring the yield of Ps atoms.

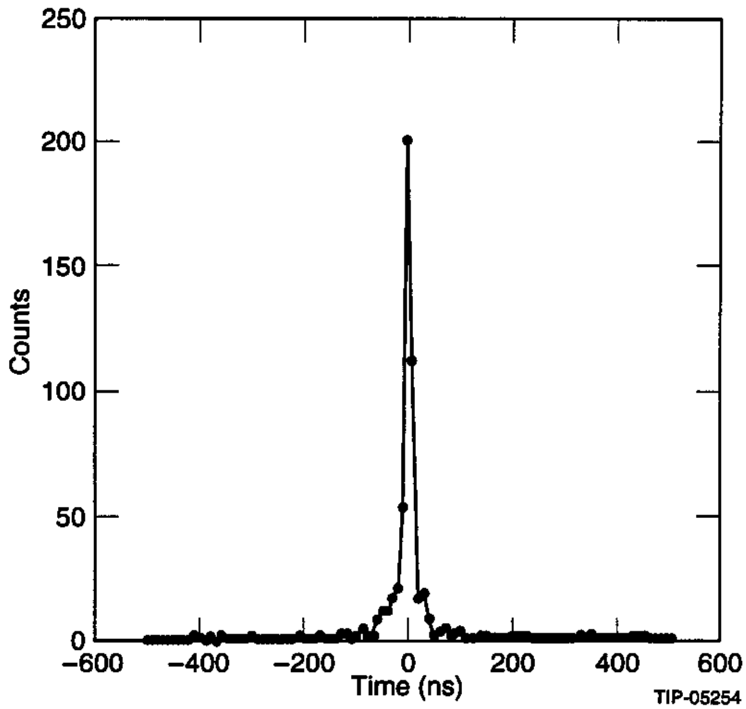

Figure 3. Coincidence signal of the two NaI detectors.

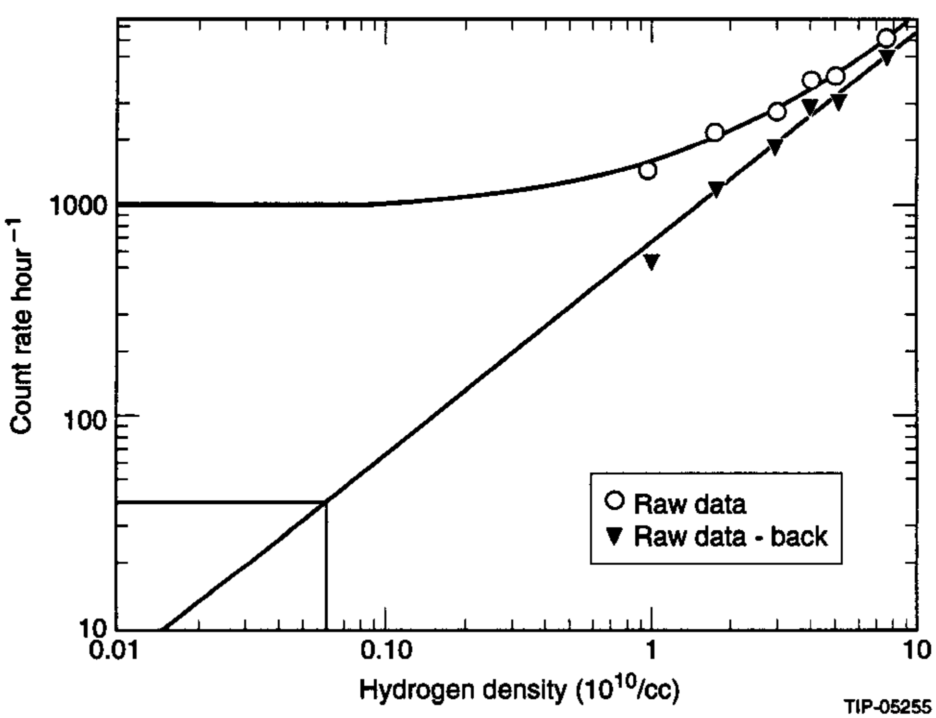

Figure 4. Coincidence count rate as a function of the Hydrogen density.

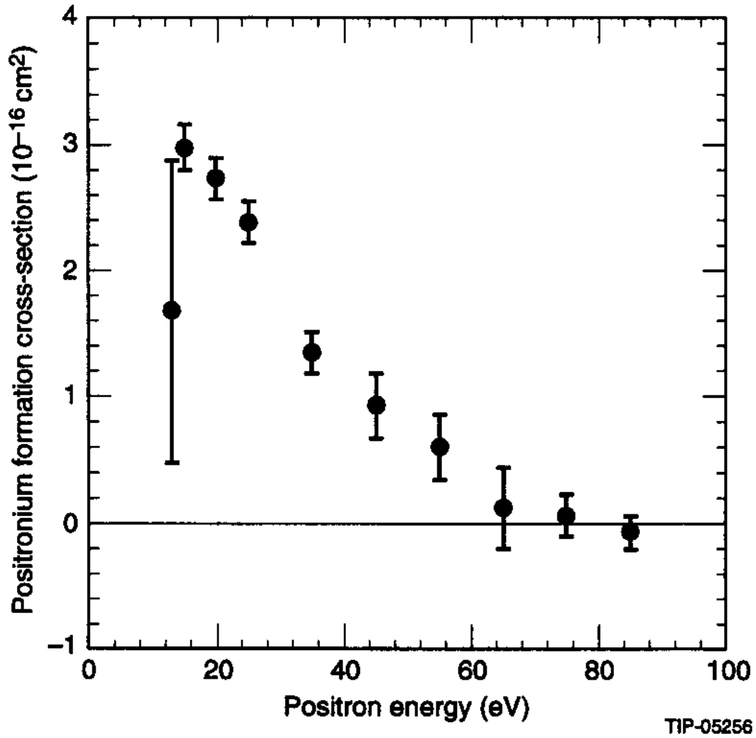

Figure 5. Positronium formation cross section of H^2 versus positron impact energy (from Ref. 4).

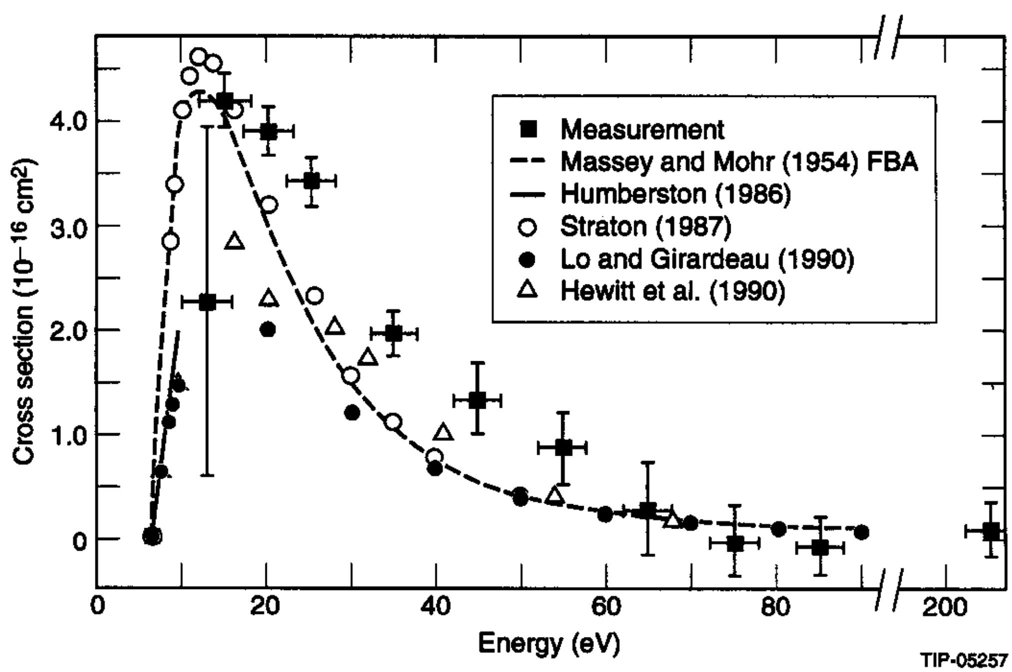

Figure 6. Positronium formation cross section of H versus positron impact energy (from Ref. 5).

4.0 THE E+ BEAM FOR THE SSC EXPERIMENT

The e^+ beam under construction for the SSC experiment is shown in Figure 7. It includes a source/moderator section, two E × B filters, a e^+ trap, an experimental section where the SSC cryostat can be inserted, and finally an electrostatic mirror. In the discussion given in this section we disregard the presence of the trap.

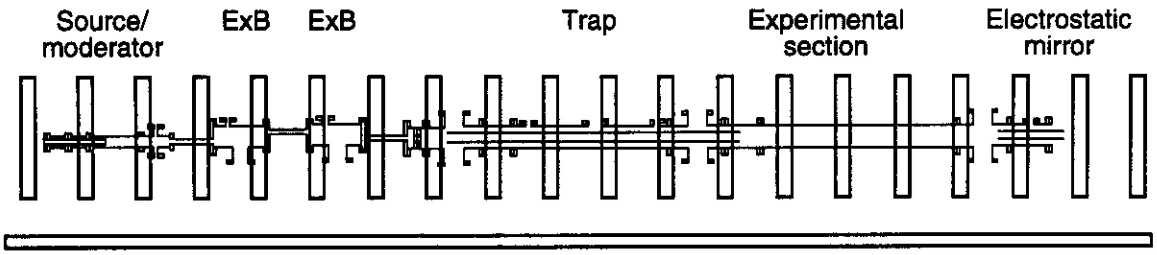

Figure 7. The design of the low energy positron beam line to be used to determine Hydrogen density in the SSC tubing (see text).

A 45 mCi ^{22}Na which is available at BNL will be used in combination with a tungsten moderator to generate the low energy e^+ beam. Referring to practical experience it is safe to assume a moderation efficiency of 2×10^{-4}, which will generate 1.5×10^5 e^+/sec. The e^+ are transported by an axial magnetic field of 50–100 Gauss produced by a set of Helmholtz coils. This magnetic field is also important as it insures that the e^+ cannot interact with the SSC tubing unless Ps is formed due to e^+ collisions with the rest gas. In order to separate the low energy e^+ from the β^+ not stopped in the moderator, the beam passes through two E × B filters. Another purpose of the E × B filters is that it allows us to effectively shield the experimental section from the ^{22}Na source. The beam then traverses the experimental section and enters the electrostatic mirror which reflects the beam back to the experimental section and finally the beam is dumped in the second E × B filter. In this way the true e^+ intensity for the pressure measurement is twice the actual number of the e^+. By taking r_i as the radius of the SSC cryostat and r_d as the radius of the NaI detectors we can rewrite Eq. (1) as

$$R = \varepsilon^2 \frac{r_d^3}{2 r_i^2} \sigma n I_{e^+} = \varepsilon^2 r_d^3 \;\; 8 \times 10^{-5} \qquad (2)$$

where ε is the attenuation factor of the annihilation ray through the construction materials of the SSC cryostat. For the numerical evaluation we have used $r_i = 15$ cm. From Eq. (2) we can calculate the minimum radius of the NaI detectors required to obtain about 100 coincidence counts per hour as

$$r_d = 7.2 \times \varepsilon^{-2/3} = 13.9 \text{ cm} \qquad (3)$$

where we have taken $\varepsilon = 0.37$ which accounts for the present design of the SSC cryostat. At BNL we have available ten 5 in. × 5 in. NaI detectors which when combined represent a detector radius r_d equal to 14 cm.

It is possible to enhance the sensitivity somewhat by transferring some of the e^+ velocity parallel to the magnetic transport field into the perpendicular direction. To do this will demand a slight modification of the acceleration stage in the source/moderator section. Furthermore the e^+ should start in a weaker magnetic field and then enter the interaction region where the transport field increases to about 200 Gauss. The result of such an approach is that while keeping the total energy constant the effective length of the interaction region is increased by a factor $v_o/v_{||}$, with v_o being the e^+ speed and $v_{||}$ the velocity parallel to the transport field. It is estimated that the signal rate may be enhanced a factor of 5 by this method.

5.0 ENHANCEMENT OF THE PRESSURE SENSITIVITY BY INCLUDING A TRAP

The purpose of the trap is to enhance the gas density sensitivity by making it possible for e^+ to make many passes through the interaction region. The trap consists of five cylindrical elements numbered 1 to 5 (see Figure 8). The elements 1 and 5 are connected to ground. Below we give a step-by-step description of the working principle of the trap.

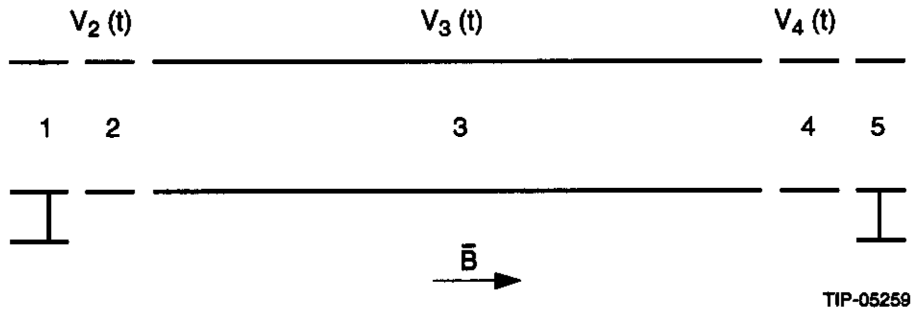

Figure 8. Five elements of the trap (see text).

Consider first a filling sequence of the trap. Assume the e^+ have a kinetic energy of 30 eV when they exit the second E × B filter. Let $V_2 = V_3 = 29$ V and $V_d = 50$ V. If an e^+ enters the trap at this stage it will move toward the end of the trap with a kinetic energy of 1 eV and become reflected at element 4 and move toward the entrance where it will exit the trap. However, suppose that V_3 is lowered to 28 V in a time shorter than the e^+ turnaround time, t_t, in the trap then the e^+ is trapped. Now assume that a second e^+ enters the trap then it will have a kinetic energy of 2 eV while in the trap and consequently V_3 must be lowered to 27 V in a time shorter than was the case for the first e^+. The length of the trap is 1 meter which yields $t_t = 3.3\ \varepsilon^{-1/2}$ (eV) μsec where ε is the kinetic energy of e^+ in the trap. If this process is continued until V_3 decreases to –70 V which takes 61.5 μs the trap will on the average contain 9 e^+ with a uniform distribution of kinetic energy from 1 to 100 eV. At this stage V_2 is raised to 100 V while V_4 is lowered to 29 V. Now those e^+'s with ε = 100 eV will be able to escape from the trap and once they have passed element 5 their kinetic energy will be reduced to the original 30 eV. After a time corresponding t_t for those e^+, V_3 is increased by 1 V whereby those e^+ having a kinetic energy of 99 eV in the trap can escape and so on. Once V_3 has been increased to 29 V the whole sequence is repeated. Figure 9 shows V_3 as a function time for 1 cycle. To generate this function we have available an arbitrary wavefunction generator.

At the time when V_4 is lowered to 29 V, positrons which were moving forth and back in the experimental section can now reenter the trap through the back door but will be reflected by V_2, now at 100 V, and therefore be forced back to the experimental section again, however with an increase of their kinetic energy by 1 eV. This increase is caused by the increase of V_3 which takes place during the time these e^+ spend in the trap. Due to this heating effect, the wise way to operate the trap may be to inject the e^+ into the trap at an energy of about 10 eV then when the trap is open viz. V_4 equal to 10 V the e^+ will heat up to about 30 eV (which is near where the Ps formation cross-section peaks) and remain at that energy for the next accumulation period. The next time V_4 is dropped to 10 V the e^+ will heat up further. When their energy reaches 100 eV they will be able to pass the second element $V_2 = 100$ V and will therefore be lost from the trap.

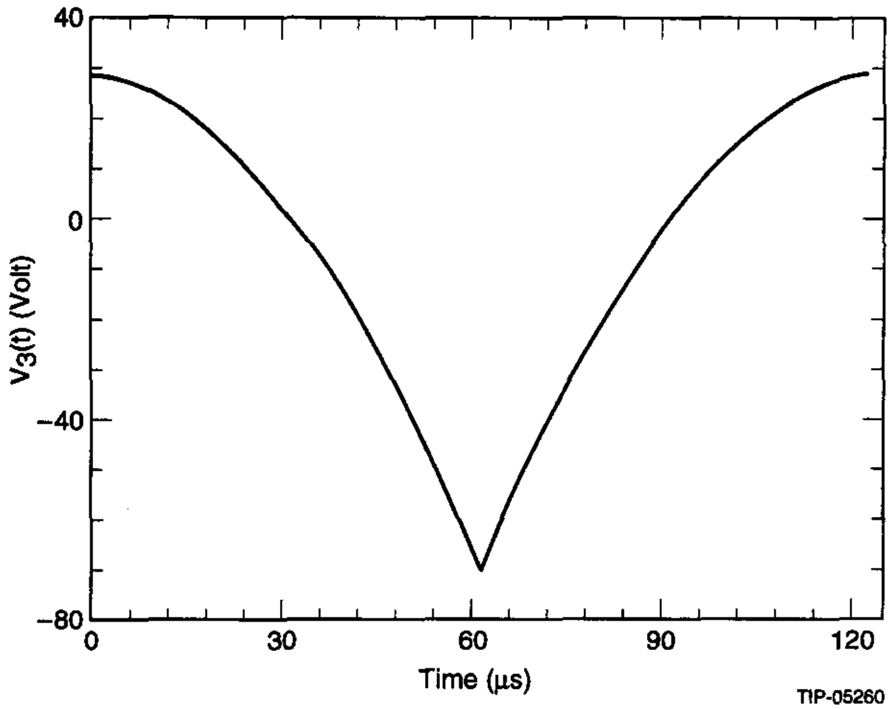

Figure 9. Variation of V_3 as a function of time.

During the period when the trap is open to the experimental section no accumulation can take place so only 50% of the low energy e^+ can be used. The turnaround time in the experimental section is about 2 µsec for $\varepsilon = 30$ eV. When the trap is open the average turnaround time is 3 µsec. The total net gain in the signal rate is approximately 30 where we have taken into account that only 50% of the e^+ are available for the pressure measurements.

6.0 SIGNAL-TO-NOISE RATIO AND CALIBRATION

In the discussion of the signal-to-noise ratio it is assumed that the ^{22}Na is shielded well enough such that we can ignore problems with 1.28 MeV gamma rays from ^{22}Na source. Thus, we only have to deal with random coincidences which are related to the single count rates of the NaI detectors, N, as

$$B = \tau N^2 \tag{4}$$

where τ is the resolution time of the coincidence setup. By taking τ = 20 nsec (see Figure 3) and demanding $B < 3 \times 10^{-2}$ sec^{-1}, which is about four times less than the expected signal rate at a density of 6×10^8/cc for the case where the trap is not used, we obtain

$$N < \sqrt{\frac{3}{2} \times 10^6} = 10^3 \, \text{sec}^{-1} \tag{5}$$

which poses no restrictions on the measurements. Also cosmic rays are not a concern at this level of the signal rate and can be vetoed out fairly easily.

The approach to take in making absolute density measurements depends on the accuracy needed. If uncertainties of the order of a factor of 2 are acceptable, it is probably safe to trust the Ps formation cross section measured by others. If the trap is going to be used it will be necessary to compare the signal rate, at high gas density, for a straight through beam to that when the trap is operational.

If high accuracy of the density measurements is needed, a calibration can be made by setting up a test experiment in which first e^- are used to determine the gas density by using accurate measurements of, for example, the ionization cross-section. Then the e^+ beam can be passed through the same interaction region and the Ps formation signal can be recorded. An e^- beam can be obtained from the moderator simply by reversing the polarity of all of the applied voltages.

7.0 SUMMARY AND CONCLUSION

An approach to determine the gas density in the SSC tubing using an e^+ beam has been described. In its simplest version this machinery can measure densities as low as 6×10^8 /cc within a very reasonable time. We have discussed the use of a simple trap which can enhance the sensitivity by at least an order of magnitude. Also, it is worth pointing out that if more sensitivity is needed, we have the option of replacing the tungsten moderator with that of solid Kr which will increase the e^+ intensity by one order of magnitude. All the necessary equipment is available at Brookhaven and we have the necessary expertise from several years of running a low energy positron beam in which solid Ne acts as a moderator.

REFERENCES

1. P. J. Schultz and K. G. Lynn, *Mod. Rev. Phys.* **60**, 701 (1988).
2. E. Gramsch, J. Throwe and K. G. Lynn, *Appl. Phys. Lett.* **51**, 1862 (1987).
3. A. P. Mills, Jr. and E. M. Gullikson, *Appl. Phys. Lett.* **49**, 1121 (1986).
4. L. S. Fornan, L. M. Diana and P. A. Coleman, *Phys. Rev. Lett.* **51**, 2276 (1983).
5. W. Sperber, D. Becker, K. G. Lynn, W. Raith, A. Schwab, G. Sinapius, G. Spicher and M. Weber, *Phys. Rev. Lett.* **68**, 3690 (1992).